The phases of strongly interacting matter in heavy ion collisions

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Abstract. In ultrarelativistic heavy ion collisions the produced high temperature, high energy density state will cross different phases of the strongly interacting matter. The original idea of quark-gluon plasma formation has been evolved and the weakly interacting gaseous state of massless partons has been replaced by the picture of strongly interacting massive constituent quarks. Experimental results at SPS and RHIC supports this idea. We discuss the phases at LHC energies.

INTRODUCTION

Ultrarelativistic heavy ion experiments at CERN Super Proton Synchrotron (SPS) and BNL Relativistic Heavy Ion Collider (RHIC) focus on the production of the Quark Gluon Plasma (QGP) state, which is described by the theory of Quantum Chromodynamics (QCD). The formation of this state was suggested 25 years ago [1]: with increasing collisional energy the produced energy density in the center of heavy ion collisions may reach a critical value, where proton and neutron degrees of freedom are melted and quarks and gluons determine the properties of the produced hot matter [2, 3]. Theorists have been expected a first order *"nuclear matter ↔ QGP"* phase transition with large latent heat at finite density and second order phase transition at zero baryon density. This latent heat is connected to the disappearance of the massive hadronic states and the formation of a weakly interacting plasma state of massless partons. With increasing collision energy simply the temperature of this plasma state would have been increasing.

However, in the mid-90's Pb+Pb collisions at CERN SPS did not show clearly this phase transition and the formation of the weakly interacting QGP, although the necessary energy concentration has been reached. 'Compelling evidences' of the transition (strangeness enhancement, melting of charmed mesons, etc.) have been collected [4], but the properties of the produced quark matter were not identified. Experimental data forced to replace the bulk description of the above phase transition with microscopical models. Quark coalescence became one of the most successful idea [5]. This model is based on quasi-particles, namely massive constituent quarks [6, 7], and the first order phase transition was successfully replaced by a cross over transition with negligible latent heat. This 10 years old finding is supported by recent lattice-QCD results at finite baryon densities [8], where the first order phase transition ends at finite temperature and density. The experimentally accessible regions belong to the cross over phase transition region. The presence of quasi-particles enriched the phase structure at high T.

STRONGLY INTERACTING MATTER AND QUASI-PARTICLES

The analysis of SU(3) lattice QCD results on equation of state in a thermodynamically consistent quasi-particle picture [7] yielded a description of a deconfined state, where the basic degrees of freedom are quarks, antiquarks and gluons with the usual color and spin degrees of freedom (e.g. transverse gluons), but with an effective thermal mass and width, generated by many-body interactions. The consequences are the following:

1. The effective thermal masses are large around the critical temperature T_c, and they are linearly increasing with the temperature (e.g. in case of $N_f = 2$ one obtains $M_{g,\infty}(T_c) \approx 500 \; MeV$ and $M_{q,\infty}(T_c) \approx 330 \; MeV$, see Ref. [7]).
2. The effective strong coupling constant, α_{eff}, is large around T_c, the system is strongly coupled. In parallel, the effective width of the quasi-particles is very small, $\Gamma \sim g^2 T \log(1/g)$, thus massive quarks are well-defined objects around T_c.
3. The gluon number is suppressed, because massive gluons are heavier than the massive quarks. This suppression is large around the critical temperature (for $N_f = 2$ the ratio is $N_g/(N_q + N_{\bar{q}}) \approx 1/3$ around T_c), thus quarks and antiquarks dominates the matter. We will call this state as Quark-Antiquark Plasma (QAP).
4. The QAP phase is relatively dilute: the densities of the massive quarks and gluons are much smaller than in the massless case (one obtains factor 2.5 for quarks and factor 5 for the gluons in case of $N_f = 2$).
5. The speed of sound is large around the critical temperature, $c_s^2(T_c) \approx 0.15$, which implies fast expansion and fast dynamical evolution of the QAP phase.

Such a massive quasi-particle picture was successfully applied to describe the soft particle production at CERN SPS and BNL RHIC [5, 9, 10]. Even more, high-p_T data were reproduced successfully by quark coalescence at RHIC energies, explaining the anomalous antiproton/pion ratio [11, 12, 13] and the scaling of elliptic flow [14].

Strongly interacting quarks and antiquarks can form color mesonic bound states inside the deconfined matter [15], and further complicated objects may appear, thanks to the strong effective coupling constant between massive quarks and gluons. The presence of such a color bounded complex objects can be responsible for the appearance of a liquid-like behavior of the QAP phase around the critical temperature. Furthermore, these heavy compounds are able to drag the even heavier charm quarks and generate a common quark flow, as it was observed at RHIC [10, 16].

As the temperature is increasing, the effective strong coupling constant is decreasing, finally it overlaps with its perturbative QCD value around $T \sim 3\,T_c$. In parallel, the width of the quasi-particles is increasing: when $\Gamma \sim M$, then quasi-particles become ill-defined, they split into the original degrees of freedom, namely massless quarks and gluons. Since this is a continuous change in the properties and the number of degrees of freedom does not change, there is a smooth phase transition between QAP and QGP, the strongly interacting QAP phase is the low temperature manifestation of the weakly interacting QGP. This smooth change is expected around $T = 400 - 450$ MeV. At RHIC we may reach higher temperature in the early stage of the heavy ion collisions, however the cooling and expanding QGP state will be converted into QAP and hadronize from this state. This is the reason, why coalescence models work successfully at RHIC energies.
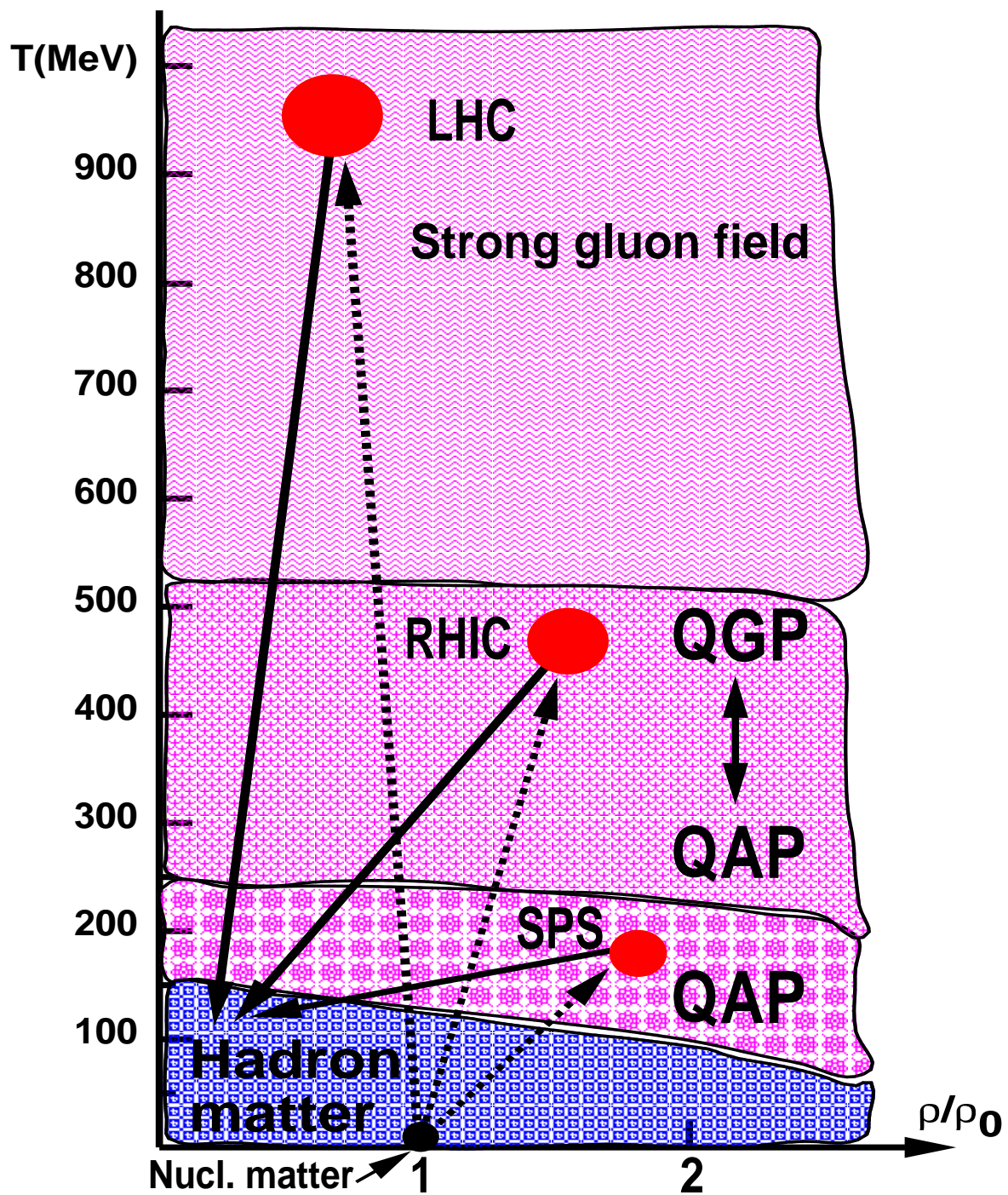
FIGURE 1. The different phases of the strongly interacting matter. The dotted and solid lines indicate the compression and expansion path of the heavy ion collisions at different energies.

At LHC energies we can reach such a high energy concentration, when the gluons will dominate the produced matter and a Yang-Mills black body radiation may appear in heavy ion collisions. This phase is very interesting, because at high gluon density we expect the formation of a classical gluon field and special saturation behaviors can be studied experimentally. It is important to investigate, if we can reach such a high temperature in real heavy ion collisions, because direct particle production from strong (abelian and non-abelian) fields may generate much lower temperature [17].

Figure 1 summarizes the discussed phases in a temperature—density plot. In fact there are no sharp boundaries between the different phases, they smoothly overlap with each others. The dotted and solid lines indicate the path in heavy ion collisions at different energies. To verify our picture, we can consider the results of jet-tomography analysis [18] about the measured color charge densities at different energies.

Figure 1 displays static phases of infinite matter. Recently we are investigating those properties of the strongly interacting matter, which can be verified and determined from microscopical models, e.g. heating, viscosity in molecular dynamics simulations [19].

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